Research Article

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Characterization of the effects of a plasma injector driven by AC dielectric barrier discharge on ethylene-air diffusion flame structure

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Abstract: A dielectric barrier discharge plasma controlled diffusion flame experimental system was built based on the designed coaxial swirling plasma injector. The air plasma was generated within the annulus gap of the injector by alternating current dielectric barrier discharge. The discharge characteristics and power of plasma injector under different actuation intensities and air flowrates were measured. Through the measurement techniques, such as schlieren imaging, broadband chemiluminescence image and CH^* chemiluminescence, the effect and mechanism of plasma on ethylene-air normal diffusive jet and flame was explored. The results showed that a large number of filamentary discharge channels are formed in air plasma. The increase of air flowrates weakened the intensity of discharge to a certain extent. The induced jet generated by the plasma can short the laminar length of the ethylene-air jet, accelerate the transition of the flow jet, enhance the turbulence and the mixing of the fuel and the oxidizer. The higher the actuation intensity, the shorter distance of the cold jet transition zone, the higher the jet turbulence. Depending on the aerodynamic and kinetic effects, plasma can improve the stability of ethylene-air diffusive flame and reduce the lift height between the flame root and injector. The plasma can also expand the flammability limit of ethylene-air flame and make the flame ignited under some conditions that could not be. In addition, the CH^* chemiluminescence shows that, in a certain range of discharge voltage, the heat release distribution can be changed on both sides of the flame, and its representative length are generally reduced as the voltage rises. On the contrary, the

overtop voltage could lead to a decrease of flame heat release.

Keywords: plasma assisted combustion, ethylene, DBD, diffusive flame, coaxial injector

1 Introduction

Rocket engines are widely used in spacecraft, but hydrazine fuels are mostly used as propellants currently, which are highly toxic and pollute the environment. With the rapid development of human space activities, the non-toxicity spacecraft propellants has become an inevitable trend. At present, hydrogen is regarded as an ideal propellant fuels for spacecraft engines due to its easy ignition and non-polluting products [1, 2]. However, hydrogen has a very low boiling point and low density in the case of liquid hydrogen, which in turn leads to an increase in the fuel reserve space required for the aircraft and a reduction in flight payload [3]. As a result, hydrocarbon fuel has become the preferred fuel scheme for active and future new rockets or aircrafts because of its high calorific value, high density, high specific impulse and low pollution [4, 5].

Coaxial injectors are widely used in power system for its simple structure, good chamber compatibility, high combustion safety and stability [6–8]. However, the fuel and oxidizer are ejected from separated tubes and mixed at the outlet of the injector, which results in a serious deviation of local equivalence ratio from the flammability limit, and the fluctuation of fuel and oxidizer flowrate may seriously affect the flame stability in a practical operating condition. In addition, for reusable aircraft, there is a need for multiple ignition. How to ignite under the lean burn equivalence ratio is also one of the urgent problems to solve. In this case, active or passive control of fuel/oxidizer jet flows generated by coaxial injectors is great significance. Although the control methods are different, they can improve the mixing and spreading of the jet by modify the geometry of the outlet jet. In addition, the active flow con-

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trol device allows adjustment of control parameters based on real-time operating conditions as compared to passive control devices that modify flow in a permanent manner.

Relying on the particular features of thermal, kinetic, and transport effects, plasma assisted combustion technology can shorten the ignition delay, enhance combustion efficiency and stabilize flame combustion [9–13]. It is worthwhile to study how to solve the combustion difficulties of hydrocarbon fuel and enhance the mixing of jet by using plasma assisted combustion technology. Several researches have paid attention to the application of plasma to improve the ignition of fuel/air mixtures [14–16], increase flame propagation speed [17, 18], enhance flame stabilization [19, 20] and extend flammability limits [21, 22]. A DBD actuator was designed for the control of a round turbulent air jet [23], the results show that, the electrohydrodynamic forces near to the dielectric wall could cause "electric wind" with the discharge of the DBD actuator, which makes the natural attached turbulent flow separated. In [24], an AC dielectric barrier discharge reactor was designed with quartz as dielectric material. The outer wall of the quartz tube was meshed with HV electrode, then the discharge was applied to the propane before it mixed with air. There is a 6 cm long mixing zone above the inner tube and inverse diffusion flame will form after ignition. With the increase of plasma power, propane flame originally adsorbed at the inner ejector gradually inhaled into the mixing zone, and the flame was elongated. The author considers that the phenomenon was related to an increase in the flame propagation rate caused by plasma. The same AC-DBDPA and burner geometrical configuration were used by Xu et al. [25], replacing propane with CH_4 . The above experimental results verified that it is the edge electric field that causes the acceleration of methane-air mixing process. De Giorgi explored the effect of plasma on the stability of CH_4 -air lean burn flame by intensified CCD imaging technology [26, 27]. Based on the design of ceramic coaxial injector, the influence of plasma control on methane-air combustion flame with AC dielectric barrier discharge was studied by Zhou et al. [28, 29]. It shows that the plasma significantly allows stabilizing the flame under lean conditions. Moreover, the impact of plasma on the flame is strongly dependent on the DBD configuration, in particular on the standoff distance and the flow conditions.

Above all, on the one hand, most plasma assisted jet flame is based on industrial burners configuration, which is relatively rare in spacecraft or aircraft engine system. On the other hand, most plasma controlled diffusion flame experiments mainly use methane and propane as fuel, the focus on ethylene diffusion flame is less. Accordingly, an alternating current dielectric barrier discharge injector is

designed and built to reasearch the internal mechanisms of plasma control diffusive flame stabilization. The flame behavior was investigated by photographs and chemiluminescence imaging through a digital camera.

2 Experimental setup

2.1 Plasma injector

The plasma coaxial swirl injector actuator is the core device of the whole flame experiment system. The plasma nozzle is derived from the rocket engine nozzle and redesigned to facilitate the experiment. The injector consists of three parts: the center stainless steel tube, the intermediate quartz tube, and the outer stainless gas collecting chamber. The intermediate quartz tube is connected with the gas collecting chamber by threads and sealant is added to realize sealing. Two 'O' shaped sealing rings are also used between the quartz tube flange end and the gas collecting chamber to prevent axial leakage. The center and the quartz tube are fixed by the bottom bolt connection, where a tight fit is adopted.

The center tube has an inner and outer diameter of 5 mm and 7 mm. As the ground electrode, the outlet end has a 30° angle to the axis. For quartz tube, which works as the dielectric barrier layer, the inner and outer diameters are 9 mm and 15 mm, respectively. The mixing region, which is the zone between the top ends of the center and quartz tube tubes, is 5 mm long. It is the zone in which the reactants mix themselves and prevent arc formation over the lip of the injector to a certain degree. A 45 mm length copper, which is the high-voltage electrode, surrounds the outlet part of the quartz tube. The plasma injector and its configuration, cross section image are presented in Figure 1. According to the working condition, the swirl number of the injector is 0.11–0.51.

2.2 Experimental system

The experimental set-up consists of: a plasma injector device, propellant supply system, high voltage source with discharge control and measure devices, and combustion control and diagnostic system. The whole experimental system are presented in Figure 2. Pure ethylene (99.99%) and dry air (volume ratio of N_2 to O_2 is 79% : 21%) serve as the gas sources. The fuel and oxidizer flowrates are controlled by the volume flow controllers and are calibrated for air and ethylene with a control accuracy of 2.5%ffl.

Figure 1: Configuration of plasma injector

The high-pressure fuel and oxidizer are decompressed by specific valve, and then enters into the plasma injector through manual valve, flowmeter, pressure gauge and magnetic valve. The controlling computer sets the working sequence of the magnetic valve to accurately control the sup-

ply of air and ethylene. Ethylene is ejected from the center tube directly, while the oxidizer air flow jets out through the annulus gap between the center tube and the quartz tube.

The HV generator was the CPT-2000K plasma generator, which can produce 0–30 kV voltage with actuating frequency of 5–30 kHz. A sinusoidal waveform actuation signal with different voltage amplitudes and a frequency of 10 kHz was applied to the copper foil surrounds the quartz tube. The voltage across the electrodes is measured with a Tektronix (P6015A) high-voltage probe. The current through the electrodes is measured with a Pearson coil (Model 6595). An oscilloscope (Agilent DSO-X 3024A) were used to retrieve the voltage-current characteristic as a function of time and the electrical power dissipation.

The most intuitive display method of flame shape is to take a digital picture through the camera to obtain its visible image. The visible flame appearance was captured using a with a Canon 7D Mark II camera equipped with a Canon EF50mm f/1.8 STM Lens. Since CH radical is an important intermediate reaction product in the combustion process of hydrocarbon fuels, which mainly distributes in the reaction zone, its CH* chemiluminescence has a linear relationship with the heat release rate. Therefore, during the experiment, the CH* chemiluminescence of flame is obtained by camera together with a 430 ± 6 nm bandpass filter (passing 85% of the light emission).

In order to visualize the ethylene-air jet flow, a 'Z' shape arrangement schlieren system is established. The schlieren imaging system consists of xenon lamp, adjustable slit, focusing and reflecting mirror, knife edge, and the other instrument bases.

3 Results and discussion

3.1 Electrical characteristics and discharge images

Figure 3 shows the effect of voltages on waveforms with $\dot{V}_{air} = 2.0$ L/Min, 4.0 L/Min and 6.0 L/Min, respectively. The discharge, produced by plasma injector under the action of AC power supply, formed a large number of pulsed currents. Within each cycle, discharge occurs in the rising and falling edges of the voltage. Irregular tip pulses occurred near the peak of the current, which have the characteristics of typical filamentary discharge.

For a certain air flowrate, the current peak value and pulse number rise with increasing voltage, and the displacement current increases notably. It can be seen that

Figure 2: Schematic of the plasma injector flame control experiment

higher voltage makes the air dielectric ionized more sufficiently, which leads to the increase of micro-discharge channels.

Keeping the actuation voltage, with the increase of air flowrate, the amount of pulse current decreases gradually, which is more obvious at low excitation voltage. When the $U_d = 19$ kV, the influence of air flowrates on the discharge characteristics is weakened. The reason for this phenomenon is that, under the same outlet cross-sectional area, the higher the air flowrates, the shorter residence time of the air pass through the injector discharge gap, the lower the degree of air ionization.

Figure 4 presents the photographs of the discharge captured in the annulus gap of the injector, which correspond to the operation conditions given in Figure 3. The camera parameters are set to 1 ms exposure time, aperture $f = 1.8$, ISO = 10000.

$\dot{V}_{air} = 2.0$ L/Min, $U_d = 13$ kV, at this time, the discharge luminescence of air plasma is not uniform, and the filamentary discharge channel is not completely symmetrical. The discharge area presents dark purple, which means the degree of air ionization is weak. This is mainly due to the fact that, the 13 kV is not much different from the break-

down voltage of about 12.6 kV, and it is difficult to process the designed injector, which results in that the wall of the center tube and quartz tube can not be absolutely smooth, and the annulus gap is not completely symmetrical. In addition, a large number of filamentary discharge channels formed by discharge do not remain stationary in the annular gap, which rotate rapidly counterclockwise. With the increase of excitation voltage, the plasma filaments and discharge brightness in the annular gap area increases. Under $U_d = 19$ kV, the discharge brightness of the annular gap changes from dark purple to pink purple, and the discharge brightness becomes more uniform.

With the air flowrate increasing to 6.0 L/Min gradually, the overall brightness of the annular gap discharge area decreases, the alternation of light and dark shade increases significantly when the excitation intensity is low. Combined with the analysis above, this is caused by the decrease of pulse discharge channels and current with the increase of air flowrate. $U_d = 19$ kV, the influence of air flowrate on brightness intensity of annular gap discharge is gradually weakened, the discharge pattern is almost the same at three flowrates.

Figure 3: Characteristics of plasma injector under different flowrates and voltages

The average discharge power of swirl plasma injector was measured under different air flowrates. By using the waveform data of voltage and current recorded by oscilloscope, the average plasma power of two half discharge cy-

cles can be obtained by using the following equation.

$$P = \frac{\sum_{i=1}^n U_i I_i \Delta t}{n \Delta t} = \frac{\sum_{i=1}^n U_i I_i}{n} \quad (1)$$

Where n is the number of recorded data by the oscilloscope; Δt is the time interval of the adjacent data; U and I

Figure 4: Discharge image under different air flowrates, (a)-(b): $U_d = 13, 15, 17, 19$ kV

Table 1: Average power of air discharge in plasma injector, Unit:W

Voltage (kV) Air Flowrate (L/Min)	13	15	17	19
0.0	12.66	18.37	24.73	33.09
2.0	13.71	19.23	25.36	32.66
4.0	13.34	18.81	25.18	32.23
6.0	12.63	18.26	24.56	31.79

are the transient discharge voltage and current across the electrodes, respectively. The average power of plasma actuator at different air flowrates is listed in Table 1.

The discharge power of the injector increases notably as the voltage rises. There is a linear relationship between the increase of power and voltage. Compared with $U_d = 13$ kV, the discharge power at 19 kV increases by nearly 2.6 times at static air. The power is generally lower under a higher flowrate for a certain voltage.

3.2 Gas dynamical effect of plasma injector

To explore the aerodynamic effect of plasma injector in operation condition, schlieren imaging is used to capture the flowfield above the plasma injector. Considering the injection direction of ethylene-air jet, the knife edge of schlieren system is arranged horizontally. The camera exposure time is set to $1/4000$ s, aperture $f = 1.8$, ISO = 100.

The ethylene-air jet mainly consists of three stages: laminar flow, transition and turbulence, which can be seen from Figure 5. Ethylene-air jet is less affected by disturbance in ambient with the increase of air flowrate. The higher the flowrates difference between air and ethylene jet, the shorter laminar zone length of the jet, and the shorter transition time from laminar to turbulence. The

morphology of ethylene air jet changed notably with the voltage increase after the actuator turned on. Under various airflow conditions, higher voltage leads to a shorter length of laminar zone, lower height of transition zone from injector outlet, and higher turbulence of the whole jet.

When the excitation voltage is higher than 17 kV, the main distinguishable length of ethylene air jet becomes shorter, and the density gradient of the jet top region decreases obviously. The reason is that the aerodynamic force produced by plasma-induced jet acts on the original jet under high voltage, which makes the turbulence of ethylene air jet increase sharply and causes strong vibration of the main jet. On the one hand, the transition of ethylene air jet has been accelerated, the mixing of ethylene air jet is affected by high turbulence, the large-scale turbulent eddy structure in turbulent region broke up into small-scale quickly, the momentum exchange between vortices so that the energy distribution in the whole region is more uniform, and the turbulent development is more abundant. Finally, the density gradient in the top region of the main stream is smaller. Considering that the schlieren image is a visual reflection of the flow field density gradient, the reduction of the dark portion means the density gradient of ethylene and air in the mixed region decreased, which further indicates that the mixing of ethylene and air has been improved; On the other hand, the jet width at the injector exit increases, which indicates that the tangential velocity caused by plasma-induced jet enhances the transverse diffusion of ethylene air jet and indirectly reduces the penetration ability of the jet in the axial direction.

3.3 Influence of plasma on the shape and heat release of ethylene flame

3.3.1 Conditions for ethylene-air normal diffusive flame

To conduct the plasma flame control experiment, both the air and the ethylene supply valves are opened. By adjusting the air flowrate from 3-7 L/Min, then changing the ethylene flowrate to achieve a specific equivalent ratio. To ignite the mixture jet directly under the designed operation conditions, whether a flame can be formed or not is shown in Table 2. In the table, '✓' means that the jet has been successfully ignited directly, while '×' means the opposite. The conditions for successful direct ignition are as follows: three ignition attempts under each working condition, all of which can be successfully ignited and the diffusive flame can be maintained. According to the table above, three typical air flowrates of 3 L/Min, 5 L/Min, and

Figure 5: Schlieren image of ethylene-air jet under different voltages

Table 2: Direct ignition of ethylene-air jet

ER					
Air Flowrate (L/Min)	0.5	0.8	1.0	1.5	2.0
3.0	×	✓	✓	✓	✓
4.0	×	✓	✓	✓	✓
5.0	×	✓	✓	✓	✓
6.0	×	✓	✓	✓	✓
7.0	×	×	✓	✓	✓

7 L/Min were selected as the air reference flowrates, and the plasma controlled ethylene-air normal diffusion flame was tested under different equivalence ratio conditions.

3.3.2 Shape of the ethylene-air flame

Under the condition of $\dot{V}_{air} = 3.0 \text{ L/Min}$, the effect of different voltage on flame of ethylene air under five equivalent

ratio $ER=0.5-2.0$ is shown in Figure 6. The camera parameters are set to $1/20 \text{ s}$ exposure time, aperture $f = 4.5$, ISO = 100. The displayed images were the results of average of 20 photographs. The ethylene air diffusive flame is mainly bright yellow but light blue at the root. During the combustion process, a large amount of soot appears at the top of the flame, which accords with the characteristics of ethylene flame.

When $ER = 2.0$, the whole flame is slender, the root of the flame is about 16.5 mm away from the injector, with slightly shaken during combustion. After the plasma actuation turned on, the flame mainly undergoes the following two changes: first, the visible length of the flame is shortened; second, the flame lifting height is significantly reduced. Compared with no actuation, the height of the flame root at the $U_d = 13 \text{ kV}$, 15 kV is reduced by 78.7% and 84.2%, respectively. Increase the voltage, the root of the flame is attached to the injector. As one of a series of studies, the results of reference 28 showed that the effect of plasma injector on the temperature rise of jet can be negli-

Figure 6: Effect of different excitation voltage on visible image of ethylene-air flame, $\dot{V}_{air} = 3.0 \text{ L/Min}$

gible. Combined with the analysis of plasma aerodynamic effects, the reason for the above phenomenon is considered to be, on the one hand, the plasma aerodynamic effect decreases the height of ethylene air jet transition and increases its turbulence, which makes ethylene and air mix better and enlarges the flammable area at the bottom of the flame. On the other hand, the air discharge in the annular gap of the actuator can produce a variety of active particles, such as O, O₃, which can react directly with ethylene and accelerate the related branching reaction, making ethylene combustion easier. Although the ethylene flame still adsorbs to injector when the voltage is 17 kV under ER = 0.8–1.5, the adsorption capacity decreases with the decrease of the equivalent ratio. When ER = 0.5, the ethylene-air jet cannot be ignited directly without the actuation, while under the 13 kV excitation voltage the jet can be ignited, but the ethylene flame is dark red and blue. The whole flame is weak and unstable, and it is easy to extinguish. Increasing the voltage to 15 kV, 17 kV, the combustion state of has been improved, the visible length of the flame is increased, and the entire flame is more stable. At $U_d = 19$ kV, the entire flame has been adsorbed at the injector. It can be seen that the plasma actuator can expand the ignition limit of ethylene air jet.

The effect of the excitation voltage on diffusion flame of ethylene air is shown in Figure 7 when the air flowrate is increased to 5 L/Min. The initial height of the flame root from the injector decreases to 12.5 mm under ER = 2.0, the plasma decreases the height of flame root to injector by 55.2% and 56.8% respectively, the degree of height decreases was further reduced. Under ER = 0.8 and 1.0 operation conditions, with the increase of excitation voltage, the visible length of flame increases first and then decreases, and the height of flame root keeps decreasing. However, at $U_d = 17$ kV, the one side of ethylene flame has been detached from injector, and the lower the equivalence ratio, the higher the detachment height. Despite the increase of air flowrate, the flame root can be stabilized on the injector at $U_d = 19$ kV. ER = 0.5, the ignition of ethylene air jet cannot be realized under low excitation voltage at this air flowrate. It can be seen that the flame burning intensity at $U_d = 19$ kV is weaker than other equivalent ratios.

Finally, increase the air flow to 7 L/Min. At this air flow rate, the jet cannot be ignited even with plasma actuation when the equivalent ratio reached 0.5. As shown in Figure 8, ER = 2.0, at $U_d = 13$ kV, 15 kV, the reduction range is shrunken to 38.4% and 42.3% respectively, which is the smallest reduction range of flame root height under each air flow rate. Ethylene flame cannot be completely adsorbed to the injector even at $U_d = 17$ kV. ER = 1.5, the visible length of diffusive flame keeps increasing, and the

flame root height is almost equal under the excitation voltage of 13 kV and 15 kV. The instability and jump of ethylene flame becomes more and more obvious at $U_d = 17$ kV with ER = 1.0, and the phenomenon that the height between the flame root and the injector increases instead of decreasing, which has never happened in previous operation conditions. The experimental results show that plasma can improve the stability of ethylene-air diffusive flame. However, under the combined action of plasma-induced aerodynamic and kinetic effect, the overtop discharge voltage at some equivalent ratios may lead to flame instability, the voltage is not need to be as large as possible. The flame stability of ethylene recovers at $U_d = 19$ kV, and the visible flame length increases greatly.

3.3.3 CH* chemiluminescence the ethylene-air flame

CH* chemiluminescence can clearly distinguish the heat release distribution in ethylene flame. As can be seen from Figure 9, the region with strong CH* emission is the mainly heat release zone of the flame, which concentrates on the upper half of flame.

At $\dot{V}_{air} = 3.0$ L/Min, the area with heat release intensity over 150 is a shape of ellipse under ER = 2.0. When the actuator is turned on to 13 kV, the shape of the heat release zone changes to 'n' shape. There are two changes, first, the overall height of the flame heat release zone decreases, and second, the heat release from both sides of the ethylene flame increases significantly near the height of 45 mm. This phenomenon indicates that the plasma aerodynamic enhances the mixing of the internal and external jet, which increases the local ethylene concentration in the outer part of the ethylene flame, thus enhancing the combustion heat release of the flame in the region. With the increase of discharge voltage, the heat release zone keeps 'n' shape, the overall height of the heat release zone decreases continuously, and the heat release on both sides of the flame increases. At $U_d = 19$ kV, the central heat release zone of the ethylene flame inclines to the right. The possible reason for this phenomenon is that the coaxial degree of the assembled central and the quartz tube may not be completely consistent due to the high processing difficulty. It may result in discharge intensity over an average level in a local area at high voltages, which in turn causes the flame morphology to roll. ER = 1.5, the overall distribution of ethylene flame heat release under different voltage is similar to ER = 2.0.

The equivalent ratio decreases to 0.5–1.0, when the voltage is more than 17 kV, the intensity of the flame heat release begins to attenuate. This phenomenon shows that

Figure 7: Effect of different excitation voltage on visible image of ethylene-air flame, $\dot{V}_{air} = 5.0 \text{ L/Min}$

Figure 8: Effect of different excitation voltage on visible image of ethylene-air flame, $\dot{V}_{air} = 7.0 \text{ L/Min}$

Figure 9: Effect of different excitation voltage on CH^* chemiluminescence of ethylene-air flame, $\dot{V}_{\text{air}} = 3.0 \text{ L/Min}$

under certain operating conditions, plasma can enhance flame heat release within a certain range of voltage, but the jet induced by excessive voltage plays a weakening role in flame heat release. For $\text{ER} = 0.5$, the proportion of blue flame increases, and the heat release zone mainly concentrates at the root of the flame. The heat release gets higher with the voltage goes up.

The air flowrate increase to 5 L/Min , it can be seen from Figure 10 that under the action of plasma, the length and height of the ethylene flame heat release zone with a certain extent in the $\text{ER} = 1.5$ and 2.0 . Only from the image, the overall height of the heat-dissipating area is almost similar with the increase of the excitation voltage. $U_d = 19 \text{ kV}$, the right inclination of the heat release zone decreases. Under this air flowrate, when $\text{ER} = 0.8$ – 1.0 , with the voltage

increases, the trend of flame heat release distribution increases first and then decreases more clearly. The heat release intensity begins to shrink when the voltage over 17 kV . Flame heat release close to the injector at $\text{ER} = 0.5$.

As shown in Figure 11, $\dot{V}_{\text{air}} = 7.0 \text{ L/Min}$ and $\text{ER} = 1.5$ and 2.0 , the overall height of the main heat release zone of the flame increases gradually with the excitation voltage goes up to 19 kV , which is different from that of the first two groups of air flowrate conditions. $\text{ER} = 1.0$, the unstable combustion status of ethylene flame occurred. Compared with other operation conditions, the main heat release zone of ethylene flame appears at the flame root earlier. However, under $U_d = 19 \text{ kV}$, the flame burns steadily and the root of the flame sticks to the injector, the main heat release zone returns to the yellow light region. $\text{ER} =$

Figure 10: Effect of different excitation voltage on CH* chemiluminescence of ethylene-air flame, $\dot{V}_{air} = 5.0$ L/Min

0.8, Similar to other operating conditions in $ER = 0.5$, the heat release under the 19 kV voltage excitation is mainly located on the right half of the flame root.

3.3.4 Flame characteristic parameters

According to the relevant definition in [30], height of the flame center H_C and the representative flame length L_F can be obtained by summing the CH* chemiluminescence intensity within the time-averaged image in the lateral direction. After the calculation, the distribution line of CH* chemiluminescence intensity in the axial direction could be acquired. The H_C can be represented by location with maximal CH* chemiluminescence intensity. The full width

at half maximum (FWHM) of the heat release distribution line is regarded as the L_F .

The influence of plasma on the H_C and L_F of ethylene-air diffusive flame under different air flow rates is shown in Figure 12. With the increase of air flowrate, there are three kinds of changes in H_C under different actuation voltage. $\dot{V}_{air} = 3.0$ L/Min, in general, the higher the excitation voltage, the lower the height of the flame center. $ER = 0.8$ -2.0, during the plasma actuation, the maximum reduction of H_C is 13.8%, 13.3%, 23.6% and 25.7% respectively. The H_C of the flame increases first and then decreases with the change of voltage at $\dot{V}_{air} = 5.0$ L/Min. Compared with the original flame, the reduced flame center position is equal or slightly increased, which indicates that the effect of plasma on the H_C begins to fluctuate. Significantly different from the previous operation conditions, $\dot{V}_{air} =$

Figure 11: Effect of different excitation voltage on CH^* chemiluminescence of ethylene-air flame, $\dot{V}_{\text{air}} = 7.0 \text{ L/Min}$

Figure 12: Characteristics of plasma injector under different flowrates and voltages

7.0 L/Min, the ethylene and air flowrate ratio is equal to the stoichiometric ratio or above, the plasma excitation increases the value of H_C . ER = 0.8, the flame center height reaches 104mm, which is 3.8 times higher than the original flame. This is due to the enhancement of flame top combustion caused by plasma, and the main heat release zone of the flame moves up from the bottom.

Generally, with the increase of the excitation voltage to 19 kV, although the visual length of the whole ethylene flame increases, the representative flame length of the flame decreases compared with the original flame. Based on the analysis of CH* chemiluminescence image, on the one hand, the plasma disturbance on the jet prolongs the non-primary heat release zone in the middle or lower part of the diffusive flame, on the other hand, the combined aerodynamic effect and active particles stimulated by plasma leads to the concentration of the main heat release combustion region of ethylene flame. The decreasing trend of L_F is more obvious under the fuel-rich equivalence ratio. In a few cases, the L_F of ethylene flame increases after plasma is applied, and this phenomenon mainly occurs above the voltage of 17 kV. In one case, the flame itself is very unstable. After the plasma is applied, the discharge instability and the fluctuation of the flame cause an increase in L_F . In another case, a strong discharge causes the stabilized flame to exhibit the 'oblique' phenomenon explained above, which lengthens the heat release zone of the flame.

4 Conclusion

A modular plasma injector was designed, and an experimental system of plasma controlled diffusion flame with AC dielectric barrier discharge was built. Through the measurement techniques, such as schlieren imaging, digital camera technology and CH* chemiluminescence, the control effect and mechanism of plasma on ethylene/air normal diffusive jet and flame was explored. The following conclusions were obtained from this research.

Under the action of induced jet generated by plasma, the morphology of ethylene-air normal diffusive jet changes significantly with the increase of actuation voltage. Aerodynamic effect of plasma enhances mixing of ethylene and air jets. Under various air flowrate conditions, the greater the excitation voltage intensity, the shorter the laminar length of the jet, the lower the height of the transition zone from the injector outlet, and the higher the turbulence of the whole jet.

Relying on the aerodynamic and kinetic effects, plasma can improve the stability of ethylene-air diffusion

flame and reduce the lift height between the flame root and the injector. The plasma can expand the flammability limit of ethylene-air flame and make the flame formed under some conditions that could not be ignited. However, under the condition of lean burn equivalence ratio with high oxidizer flowrate, overtop excitation voltage may lead to flame instability, so the energy required for plasma combustion is not the greater the better.

According to the analysis of CH* chemiluminescence images, the combined effects of plasma aerodynamics and kinetics can change the heat release distribution of ethylene-air flame, enhance the heat release on both sides of the flame. With the increase of excitation voltage, the heat release intensity of flame increases first and then decreases. The plasma has a certain influence on the height of the flame center and the effects is related to the air flowrate. When the air flow rate is small, the height of the flame center decreases with the increase of the voltage, while the opposite trend appears at the high air flowrate. Generally, plasma can shorten representative flame length and make the combustion area more concentrated.

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